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# Comparison of TOPEX/POSEIDON Sigma-Naught and Significant. Wave Height Distributions to Geosat

Philip S. Callahan, Charles S. Morris, and S. Vincent Hsiao

*Jet Propulsion Laboratory, California Institute of Technology*
*Pasadena, CA 91109*

Short title: Sigma0 and SWH Distributions

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*Jet Propulsion Laboratory, California Institute of Technology*
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## ABSTRACT

Monthly Ku band sigma-naught (sigma0) and significant wave height (SWH) histograms from the NASA altimeter on the TOPEX/POSEIDON satellite are derived for January through June 1993 for three latitude bands between +/- 60 degrees. The data are compared to distributions from the Geosat mission for the same months in 1987-1989. Generally, the distributions agree quite well, although there are some seasonal/hemispherical differences. The sigma0 comparison reveals an overall bias between the two altimeters with the TOPEX sigma0 higher by about 0.7 dB, which is consistent with processing differences. The SWH distributions show strong hemispherical/seasonal changes. The seasonal/hemispherical differences between TOPEX and Geosat are consistent for both SWH and sigma0. The joint distribution of sigma0 and SWH is extremely stable from month to month. The typical SWH is independent of sigma0 for sigma0 greater than about 11.5 dB. The minimum SWH for at a particular wind speed grows exponentially with wind speed. This joint distribution may be useful for understanding electromagnetic. bias. The altimeter SWH is compared to buoy values from 21 overflights of the NASA verification site near Pt. Conception California. The data agree well with an RMS difference of only 0.2 m. Altimeter sigma0s are compared to buoy wind speeds. The results are consistent with the -0.7 dB sigma0 offset from the histogram comparisons.

## 1. INTRODUCTION

Altimeters provide very precise measurements of the range from a satellite to the sea surface. In the course of making this measurement, they also produce measurements of the significant wave height (SWH, the average height of the highest third of the waves) and the normalized radar backscatter cross section (sigma0). The way in which these quantities are determined from the altimeter waveform was originally described by *Brown* [1978] and is well-described for Geosat and TOPEX in *Chelton et al.* [1989].

Because the SWH and sigma0 measurements are closely tied to the leading edge of the waveform where the range is measured, they provide diagnostic information about the accuracy of the calibration of the individual range gates and the overall system gain of the altimeter. Also, as sigma0 is sensitive to the off-nadir pointing of the altimeter, its correctness is a test not only of the altimeter hardware but also of the ground processing. Thus, checking the accuracy and stability of these measurements is a useful adjunct to other altimeter calibration activities.

In what follows, wc will discuss only (he NASA altimeter on the TOPEX/POSEIDON mission; wc will refer to it simply as "TOPEX". For SWH, the TOPEX accuracy requirement is 0.5 m or 10%, whichever is greater, The Geophysical Data Record (GDR) data resolution is 0.1 m. For sigmaO, the TOPEX requirements arc 0.25 dB precision and 1.() dB absolute accuracy. The 0.25 dB precision requirement was interpreted by the altimeter builders as resolution, so the telemetry was quantized to this level. The quantization is smoothed somewhat by corrections for off nadir pointing and sea state and for atmospheric absorption. The GDR resolution is .01 dB.

SWH and sigma0 can be tested in two general ways for accuracy: statistically by comparison to previously measured global distributions of the quantities and by comparison to buoys or other point measurement.s. The former method has the advantage of testing the altimeter over the entire range of global conditions. Because large numbers of points are tested, relatively rare anomalies may be seen. The direct comparison of sigma0 data eliminates the need for a wind speed model function to relate altimeter sigma0 to wind speed for a comparison with buoys. On the other hand, in the statistical method there is no checking of individual values, so compensating errors could mask problems; and rare occurrences may be hidden in the mass of data. Because three years of Geosat data are available with its point calibration [*Dobson et al.*, 1987], it was felt that the statistical approach would be a good first test of the TOPEX altimeter. A small set of data from a buoy near the NASA verification site near Pt. Conception, California was also used for a point comparison.

## 2. DATA INVESTIGATION

### 2.1 Methodology

Geosat and TOPEX SWH and sigma0 data were compared in the latitude bands $-60 \leq \text{lat} < -2o$, $-20 \leq \text{lat} \leq 20$, $20 < \text{lat} \leq 60$ degrees for the months January through June. The cutoff latitude of 60 degrees was chosen in order that the two data sets have approximately an equal density of points with latitude. The three bands were chosen to distinguish latitude and seasonal dependencies. The histogram interval was 0.1 meters or dB respectively. No SWH values less than 0.1 m were counted. To allow for the fact that during the TOPEX/POSEIDON (T/P) mission the CNES altimeter (SSALT) was on part of each cycle for cycles 11 through 16 (January and February) and the difference in sampling of TOPEX and Geosat, the histograms are shown as the percentage of observations in each bin.

Monthly histograms of SWH and sigma0 for the months January through June were made from Geosat GDRs on CD-ROM [*Cheney et al.*, 1993] for the years 1987-1989. It was found that the histograms for the three years were very similar, so they were combined for comparison with the TOPEX data. Only ocean data with good attitude determinations and sea surface h.eight RMS less than 10 cm were used. There are about 4 million points in each averaged monthly histogram,

Monthly histograms were also made from TOPEX GDRs [ *Callahan*, 1992]. Only ocean data with the flags Alt_Bad1 = Alt_Bad2 = O [ *Callahan, 1992]* and sea surface height RMS less than 10 cm were used. These flag settings insure that only normal ocean data are included in the counts. For the months of January and February, the typical number of "1OPEX observations in a month is 1.0 million; while for March through June the number is about 1.3 million.

## 2.2 *Significant Wave Height Distribution*

Figure 1 shows the global (~. 60 deg) SWH histograms by month for TOPEX and Geosat. No adjustment has been applied to these data. There is generally excellent agreement between the two altimeters and between the global distributions approximately 4 years apart, although there are indications of a slight shift to higher waves for TOPEX and less waves in the 1.5 -2.0 m band for TOPEX. The histograms have the expected genera] Raleigh distribution similar in shape to that of the global wind speeds [*Wentz*, 1984]. The distributions peak just above 2 meters with tails extending to wave heights of about 6 meters. Not shown in the figures are several hundred counts for heights greater than 8 meters. The highest waves found arc about 12 to 14 m. The highest waves are somewhat more frequent and higher (up to 14 m vs 12 m) in the northern hemisphere winter than in the southern hemisphere winter. We speculate that this is because of higher wind speeds driven by the greater temperature contrasts in the northern hemisphere.

Figure 2 shows SWH histograms for January, March, and June for each of the three latitude bands. A seasonal/hemispheric dependence is immediately obvious, as is the benign character of the tropics (± 20 deg) both in terms of maximum wave height and month to month changes. The southern hemisphere winter shows both a higher wave height for the peak of the distribution as well as a broader distribution with a large increase in waves above 6 meters. The southern hemisphere has almost no waves below 1 meter for all months, while such waves are common in the tropics and northern hemisphere summer. As will be seen below the trend to higher waves in the southern hemisphere is consistent with the sigma0 or wind speed distribution. The contrast between the global agreement and the southern hemisphere changes is an example of onc of the possible problems with the statistical comparison if the data arc not properly separated.

Aside from the generally good agreement between TOPEX and Geosat and the reasonable seasonal/hemispheric dependencies, several small features arc obvious on the SWH histograms: Geosat has a sharp peak in the distribution between 1.5

and 2.0 m and a significant change in the distribution below 1 m. TOPEX has dips in the counts at 3.0 m and 6,2 m. We believe that these arc instrumental effects and that the wave height distribution is basically smooth, especially near the peak. We do not know the details of the Geosat instrument or processing; but for TOPEX, the features noted occur at altimeter gate index changes. The dips are probably caused by incomplete or incorrect pointing angle/seastate corrections [*Hayne et al., 1990; Callahan*, 1992] as the gate index changes, It is likely that a similar effect causes the Geosat features between 0.5 and 0.8 m (There is a TOPEX gate index change at 0.8 m), The source of the Geosat peak at 1 .5-2.0 m is not known.

## 2.3 *Sigma0 Distribution*

Figure 3 shows the monthly global (± 60 deg) sigma0 histograms for TOPEX and Geosat. The TOPEX data have had 0.7 dB subtracted from the sigma0 values found on the GDR. This offset was determined by comparison of TOPEX data for cycles 13 and 14 (January 20 through February 8, 1993) to Geosat, assuming that year to year variations are small on a global basis. The offset is needed in order to allow usc of the modified Chelton-Wentz (MCW) wind speed model function (WSMF) [ *Witter and Chelton*, 1992] in TOPEX GDR production.

The offset is consistent with two differences between TOPEX and Geosat in the calculation of sigma0 and, thus, the. TOPEX and Geosat altimeters are in excellent agreement in measuring sigma0. First, TOPEX used a round Earth correction in the sigma0 calculation [*Callahan*, 1992] which was not used for Geosat. The TOPEX formulation results in sigma0s larger by 0.8 dB for TOPEX. If this correction were applied to Geosat, the change would be about 0.5 dB at the Geosat altitude. This accounts for 0.5 dB of the offset. Second, while both Geosat and TOPEX sigma0s were corrected for pointing angle and instrumental effects, the TOPEX values had an additional correction for atmospheric absorption applied. The atmospheric sigma0 correction mainly depends on the amount of liquid water in the line of sight as determined by the TOPEX Microwave Radiometer (TMR), although it also includes absorption by dry air and water vapor, The minimum atmospheric absorption correction is about 0.2 dB, the maximum for data without the "rain flag" set is about 0.6 dB, and the global average is about 0.30 to 0.35 dB. The combination of these two processing differences is expected to result in TOPEX sigma0s being larger than Geosat's by about 0.7 to 0.9 dB. It should be remembered that lower sigma0 corresponds to higher wind speed with 8 db giving about 18 m/s, 11 db about 7 m/s, and 16 db about 0.8 m/s (MCW WSMF).

With the offset applied, the TOPEX and Geosat data show generally excellent agreement for January through March, followed by a shift and some increase at low sigma0 for the TOPEX distribution relative to Geosat. Some of the agreement in January and February could be attributed to the offset determination, but that process used only 10 days of data from each month. Because of the limited amount of data and time span, the original offset determination could be in error by 0.2 dB. A change of 0.2 dB corresponds to a wind speed change of about 0.5 m/s for winds of 5 to 15 m/s [*Monaldo*, 988].

Figure 4 shows sigma0 histograms for January, March, and June for each of the three latitude bands. A seasonal/hemispheric dependence is again immediately obvious, as is the benign character of the tropics (± 20 deg) both in terms of maximum wind speed (minimum sigma0 about 8.5 dB except in January) and month to month changes. TOPEX and Geosat agree well in all three bands in January. In March, there is an excess of low sigma0s in the northern and southern hemispheres for TOPEX. Finally, the southern hemisphere winter of 1993 shows both a higher wind speed for the peak of the distribution (shifted from about 11 dB to less than 10 dB) as well as a broader distribution with a significant tail extending below 8 dB.

The data in Figure 4 support both the good agreement between the two altimeters and the need to separate data in order to detect seasonal/henlispheric effects. Data in Figures 2 and 4 are quite consistent in showing that the northern hemisphere and tropics were very similar between the Geosat mission and 1993, while the southern hemisphere winter of 1993 was apparently very windy, resulting in larger wave heights. All months and bands show similar distributions above about 13 dB. This is related to the difficulty in determining a WSMF for low wind speeds (< 3 m/s), i.e., at low wind speeds the backscatter is not well correlated with wind speed.

One notable feature in the TOPEX sigma0 histograms is the rapid fluctuations in the counts, particularly near the peak of the distribution. One possible explanation is that this is caused by the quantization of the telemetry to 0.2S dB. Because of the excellent pointing (during cycle 11 and onward), the pointing angle/sea state corrections to sigma0 arc fairly small ( < 0.2 dB) so that the quantization is not erased by this globally random correction.

## 2.4 *Joint Sigma0 - SWH Distribution*

Sigma0 shows large variations for low wind speeds ( < 3 m/s) which makes determining wind speed model functions difficult in this regime [*Freilich and Dunbar*, 1993; W itter and *Chelton*, 1991]. A possible distinguishing variable in this situation could be the wave height. As shown by discussions of TOPEX data [*this volume]*, the exact form of the electromagnetic bias (E MB) correction to altimeter range measurements remains controversial. The observed joint distribution of sigma0 and wave height may show different regimes of wind and waves which might be expected to have different EMB.

Figure 5 shows the joint SWH-sigma0 distribution for the TOPEX data from January through June, 1993. The bin size is 0.25 in each coordinate, The contours are in percent of the total observations (more than 7 million). The peak of the distribution (2%) is at about 11.1 dB and 2.1 m, similar to the individual sigma0 and SWH histograms. Distributions were generated for each month and were found to be so similar that they were combined. The similarity of all features of the distribution from month to month was somewhat surprising in light of the seasonal changes found in the separate SWH and sigma0 histograms.

There are several striking features of the distribution. First, the maximum ridge of the distribution makes a very sharp bend from its steep negative slope to a nearly constant SWH (1.6 m) for sigma0 greater than 11,3 dB. Second, the lower edge of the distribution rises very steeply from a sigma0 of about 11.3 dB. Third, there is an upper limit to the SWH which declines for all sigma0.

Figure 6 is a plot of the main features of the SWH-sigma0 distribution against wind speed. The minimum and maximum wave height envelopes were measured arbitrarily at the 0.01 % contour. The wind speed was determined from sigma0 by subtracting the 0.7 dB bias and then using the MCW WSMF [*Witter and Chelton*, 1991 ], except that adjusted sigmaOs less than 7.0 dB were all assigned a wind speed of 21.73 m/s. In addition to the data, Figure 6 shows functions that may represent the ridge and the minimum wave height. The sloping part of the ridge of the distribution above 8 m/s is well-represented by a power law in wind speed with exponent 1.6. This is significantly less than the exponent of 2.0 for a "fully developed sea" from the Pierson-Moskowitz spectrum *[Pierson and Moskowitz, 1964]*. The lower envelope of the distribution is well represented by an exponential in wind speed with a wind speed scale of 5,4 m/s. Finally, the upper envelope shows approximately a square root dependence on wind speed.

These features prompt the following interpretations: The ridge of the distribution represents approximately fully developed seas where the winds and waves arc in equilibrium. The fact that the SWH rises more slowly with wind speed than in the simple theory shows either that most of the waves are fetch- or duration-limited or that dissipation is more important than is assumed. The lower envelope shows the very rapid growth of SWH as wind increases and suggests that this minimum wave height is achieved in very short time. Finally, the upper envelope and the near constancy of SWH along the ridge of the distribution for wind speeds below 8 m/s shows the importance of swell in low wind speed regions. One may speculate that for wind speeds less than about 6 m/s nearly all the waves higher than 1.6 m are swell. Such regions should have a much lower EMB for a given SWH than developing or fully developed seas. Thus, this diagram could lead to a new EMB algorithm in which the relationship of the observed SWH and wind speed to this distribution is used to select different coefficients for swell, fully developed or developing seas. The distribution does not appear to offer insight into the large spread of sigma0 at low wind speeds as originally hoped.

## 2.5 Buoy *Comparisons*

The National Data Buoy Center (NDBC) buoy 46051, San Miguel, is located approximately one kilometer northwest of the NASA verification site at Texaco's Platform Harvest. Installed just prior to the TOPEX/POSEIDON launch, the San Miguel buoy provides standard buoy measurements of wind speed, atmospheric pressure, air and sea temperature, and significant wave height. The buoy sits in over 200 m of water about 12 km from the coast. *Dobson et al. [1987]* and *Monaldo* [1988] concluded that the buoy SWH measurement error can be considered negligible, while buoy wind speed measurements have an accuracy of approximately 0.8 m/s. Although the number of data points is limited for the comparison (21 ), it has the advantage that the buoy is in the altimeter footprint. In previous studies [*Dobson et 01., 1987* and *Monaldo*, 1988], spatial separation was noted as a significant source of error in such a comparison. Buoy SWH and wind speed estimates arc available once per hour and are given to 0,1 m and 0.1 m/s, respectively, in the near real time synoptic format. The wind speeds used are the extrapolated 19.5 m values. The buoy data were interpolated to the time of the T/P overflight.

Altimeter SWH and sigma0 values were interpolated to the location of the platform from one second GDR data, with the exception of cycles 2 and 3, During these early cycles, the satellite's attitude was suspect immediately over the platform. The values adopted for these cycles are representative values within a few seconds of the platform. A summary of the buoy and altimeter data are given in Table 1.

The results are displayed in the Figure 7. Figure 7a displays a direct comparison between the TOPEX altimeter and San Miguel buoy SWH. The agreement is excellent with an RMS of O. 17 m and a mean offset of -0.03 m, which is not significant, The RMS agreement is impressive given that the SWH values only have a precision of 0.1 m. "l'he difference (buoy - TOPEX) by cycle is given in Figure 7b. No trends with time are apparent.

Although the range of SWH sampled in this evaluation is only between 1.0 and 3.5 m, this ranges covers the majority of SWH values encountered in the ocean. Despite the limitations of this study, all the evidence supports the conclusion that the SWH estimates obtained NASA altimeter are accurate measurements of wave height and are well within the project specifications.

Figure 7c shows wind speed obtained from TOPEX sigma0s converted to wind speed by subtracting the bias of 0.7 dB and then using the MCW WSMF [*Witter and Chelton*, *1991]* and the difference between the altimeter and buoy plotted against buoy wind speed. There is a bias of -0.1 m/s and an RMS of 1.3 m/s. '1'here is no trend with time, except that all of the residuals in May and June are negative. Given the small number of points and the fact that the environment near the coast may be different than the open ocean, these data are not inconsistent with the offset determined from the global histograms.

## 3. DISCUSSION and CONCLUSIONS

Monthly histograms of SWH anti sigma0 separated into northern, equatorial, and southern latitude bands from January to June 1993 from TOPEX have been compared to the average of the same months for 1987-89 from Geosat. The sigma0 data show generally excellent agreement with a -0.7 dB offset for the TOPEX sigma0, except for the southern hemisphere winter, The -0.7 dB can be traced to algorithm improvements. We conclude that TOPEX is measuring sigmaOs equivalent to Geosat's to within about 0.2 dB. The SWH distributions compare well with no offset. All data show the expected seasonal/hemispheric changes. The differences between TOPEX and Geosat for the southern hemisphere winter of 1993 are consistent between SWH and sigma0 with TOPEX showing higher SWH and lower sigma0 (higher wind speed).

Some features on the TOPEX SWH and sigma0 distributions are related to known altimeter effects. Sigma0 (AGC) should be quantized to at least 0.1 dB in the original telemetry. Pointing angle/sea state effects need to correct all changes which occur at internal altimeter gate changes. The ability to see the overall calibration, instrument effects, and seasonal variations shows the utility of the statistical comparison method. It also shows that it is important to separate the data in order that seasonal or geographic changes can be separated from instrument effects,

The joint distribution of SWH and sigma0 has three main features which may help in understanding the electromagnetic bias in altimetry. The most notable feature is that along the ridge of the distribution SWH grows with wind speed to the 1.6 power for wind speeds greater than about 8 ms/s, but SWH is constant at about 1.6 m for winds less than 8 m/s. Below about 6 m/s, most of the waves are probably swell. These different wind-wave regimes should be expected to have different EMB. Separating the correction by regime should help to understand the effect and lead to lower scatter in the corrected data.

The SWH-sigma0 distribution does not help in understanding the scatter of sigma0 at low wind speeds. The sigma0 distributions show that the counts above about 13 dB do not depend on latitude or season. Together these observations suggest that it is unlikely that low wind speeds can be determined accurately from an altimeter. The seasonal/latitude variations found indicate that at least one year of global data should be used to establish a WSMF.

The TOPEX SWH and sigma0 data were compared to a small sample of buoy data from the NASA verification site. Excellent agreement for the SWH values supports the statistical comparisons in showing that TOPEX is measuring SWH within specification. The wind speed comparison also supports the statistical comparison with an offset of about -0.7 dB in sigma0.

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Author Address List:

Philip S. Callahan, Charles S. Morris, S. Vincent Hsiao
Mail Stop 300-319
Jet Propulsion Laboratory
Pasadena, California 91109-8099

E-Mail:
P. CALLAHAN/OMNET

Fax: 818-393-5184

Telephone:
P. Callahan 818-354-4753

**Figure Captions**

Figure 1: Global (t 60 deg) histograms of significant wave height for months January through June. Geosat data averaged over 1987-89 (dashed); TOPEX data for 1993 (solid),

Figure 2: Histograms of significant wave height for months of January, March, June for three latitude bands -- North: 60> lat >20, Equatorial: 20 ≥ lat ≥ -20, South: -20 > lat > -60 degrees, Geosat data averaged over 1987-89 (dashed); TOPEX data for 1993 (solid),

Figure 3: Global (t 60 deg) histograms of sigma0 for months January through June. Geosat data averaged over 1987-89 (dashed); TOPEX data for 1993 (solid).

Figure 4: Histograms of sigma0 for months of January, March, June for three latitude bands -- North: 60 > lat > 20, Equatorial: 20 ≥ lat ≥ -20, South: -20 > lat > -60 degrees, Geosat data averaged over 1987-89 (dashed); TOPEX data for 1993 (solid).

Figure 5: Joint distribution of significant wave height and sigma0 for months January through June 1993 from TOPEX data. Contours are per cent of total data, approximately 7 million points.

Figure 6: Main features of TOPEX joint significant wave height versus sigma0 distribution plotted against wind speed. Maximum SWH (triangles). Ridge of distribution (pluses) with best fit line of exponent 1.6 (solid line). Minimum SWH (open squares) with best fit exponential with scale of 5.4 (dashed line).

Figure 7: (a) TOPEX altimeter SWH versus buoy SWH at NASA verification site.
(b) Difference of altimeter and buoy SWH versus cycle.
(c) Altimeter wind speed (solid) and altimeter-buoy wind speed (open) versus buoy wind speed. Altimeter sigma0 - 0.7 dB used in model function.

# Table 1

Altimeter and Buoy Data for TOPEX Overflights of NASA Verification Site.

| cycle | GDR Sigma O | GDR SWH | Buoy Wind | Buoy SWH | Alt Wind Sp | Wind Speed Alt-Buoy |
|---|---|---|---|---|---|---|
| 2 | 13.5 | 2.2 | 2.2 | 1.9 | 2.62 | 0.42 |
| 3 | 14.3 | 1.3 | 3.0 | 1.4 | 1.79 | -1.21 |
| 5 | 11.1 | 2.7 | 6.8 | 2.8 | 9.06 | 2.26 |
| 7 | 10.2 | 2.8 | 12.7 | 2.8 | 12.98 | 0.28 |
| 8 | 11.5 | 2.0 | 4.7 | 1.8 | 7.42 | 2.72 |
| 10 | 13.0 | 1.7 | 4.8 | 1.9 | 3.4 | -1.4 |
| 11 | 12.3 | 1.8 | 5.7 | 1.8 | 5.07 | -0.63 |
| 13 | 12.4 | 3.1 | 5.6 | 3.0 | 4.78 | -0.82 |
| 15 | 11.9 | 2.7 | 5.2 | 3.0 | 6.3 | 1.1 |
| 17 | 11.4 | 2.8 | 7.0 | 2.8 | 8.16 | 1.16 |
| 18 | 12.0 | 1.9 | 6.8 | 1.9 | 5.96 | -0.84 |
| 19 | 11.2 | 2.8 | 8.8 | 2.7 | 8.95 | 0.15 |
| 21 | 10.3 | 3.5 | 11.3 | 3.4 | 12.54 | 1.24 |
| 22 | 11.4 | 1.3 | 8.4 | 1.6 | 8.16 | -0.24 |
| 23 | 10.7 | 3.2 | 9.4 | 3.2 | 10.96 | 1.56 |
| 24 | 12.8 | 2.0 | 5.6 | 1.8 | 3.92 | -1.68 |
| 25 | 13.2 | 2.5 | 5.0 | 2.3 | 3.04 | -1.96 |
| 26 | 12.9 | 1.3 | 4.4 | 1.2 | 3.6 | -0.8 |
| 27 | 11.6 | 2.6 | 7.9 | 2.5 | 7.36 | -0.54 |
| 28 | 16.0 | 1.8 | 2.6 | 1.6 | 0.91 | -1.69 |
| 29 | 10.5 | 2.6 | 12.9 | 2.6 | 11.76 | -1.14 |

Altimeter wind speed obtained from modified Chelton-Wentz model function after removing a bias of 0.7 dB from the GDR sigma0.

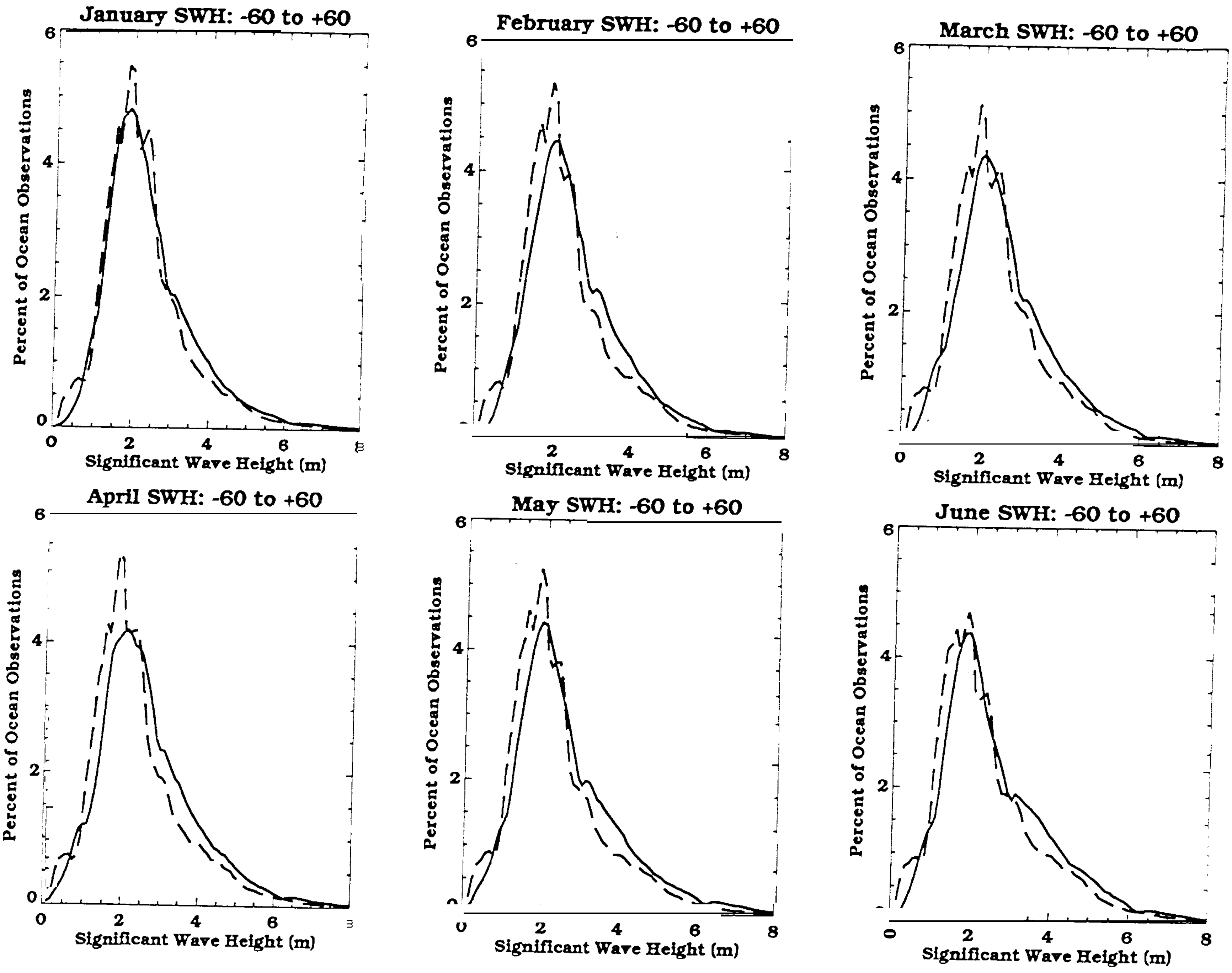

January SWH: -60 to +60
February SWH: -60 to +60
March SWH: -60 to +60
April SWH: -60 to +60
May SWH: -60 to +60
June SWH: -60 to +60
Percent of Ocean Observations
Significant Wave Height (m)

Figure 1

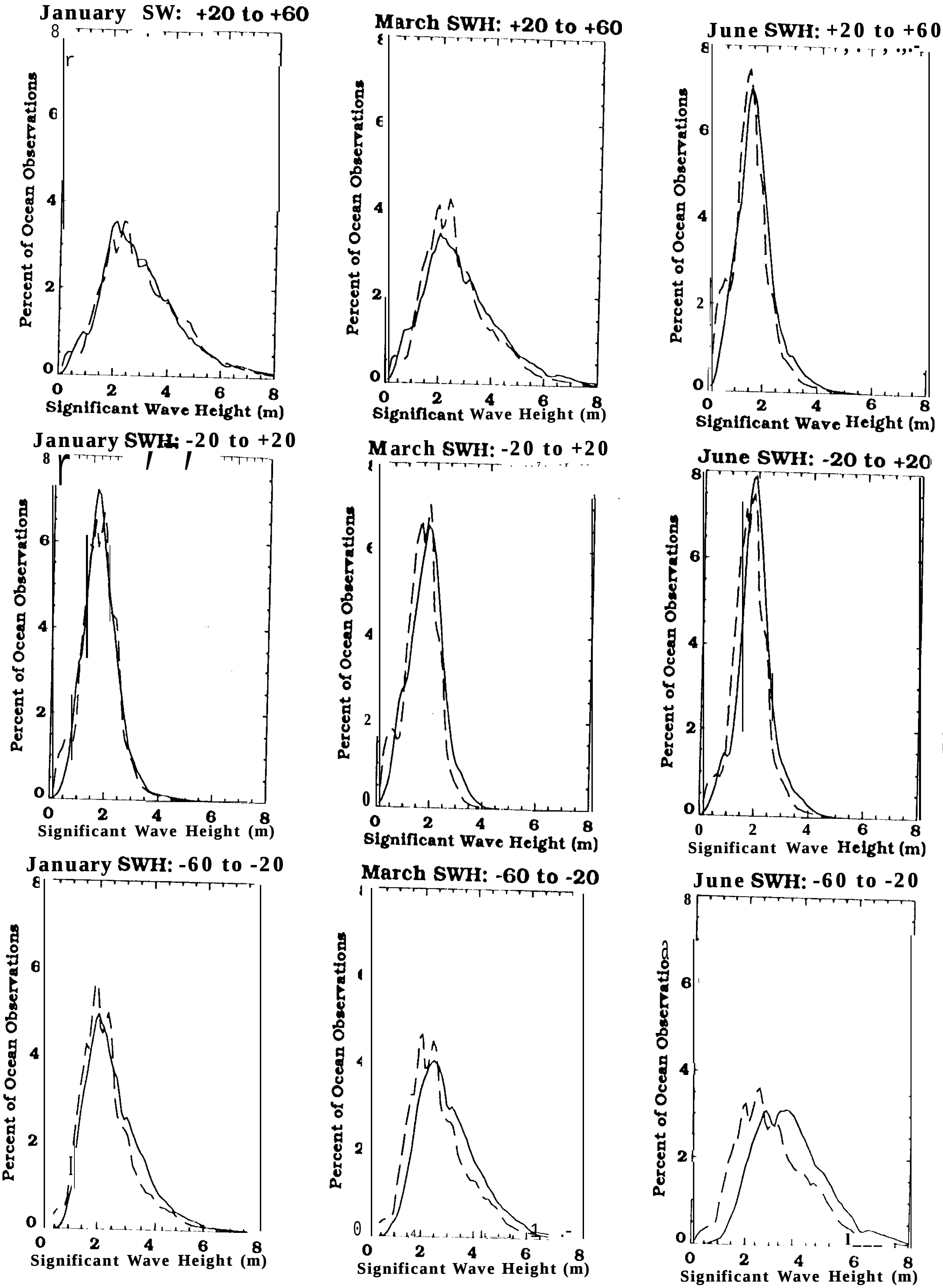
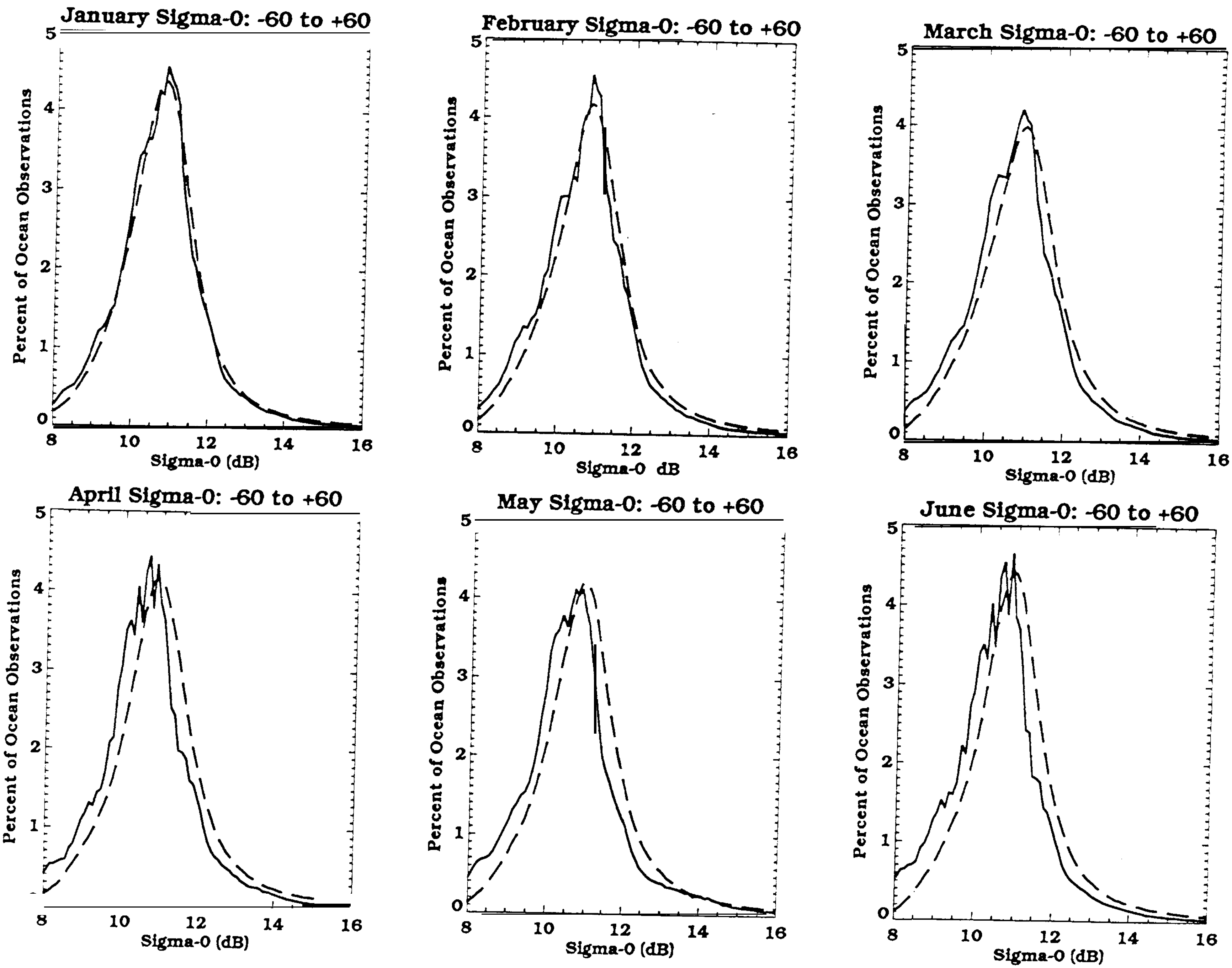
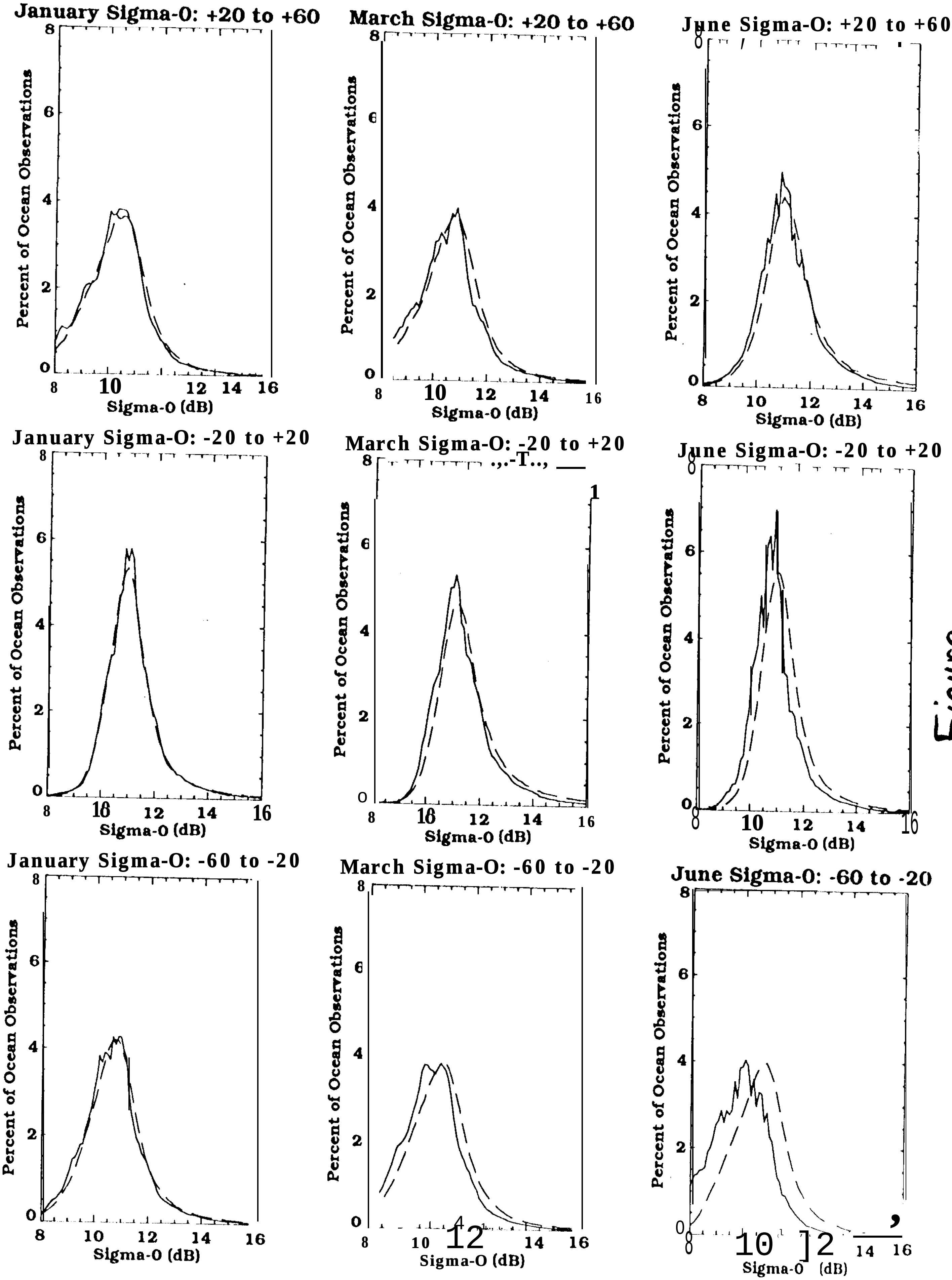

January SW: +20 to +60
March SWH: +20 to +60
June SWH: +20 to +60
January SWH: -20 to +20
March SWH: -20 to +20
June SWH: -20 to +20
January SWH: -60 to -20
March SWH: -60 to -20
June SWH: -60 to -20
Percent of Ocean Observations
Significant Wave Height (m)
0
2
4
6
8

Figure 2

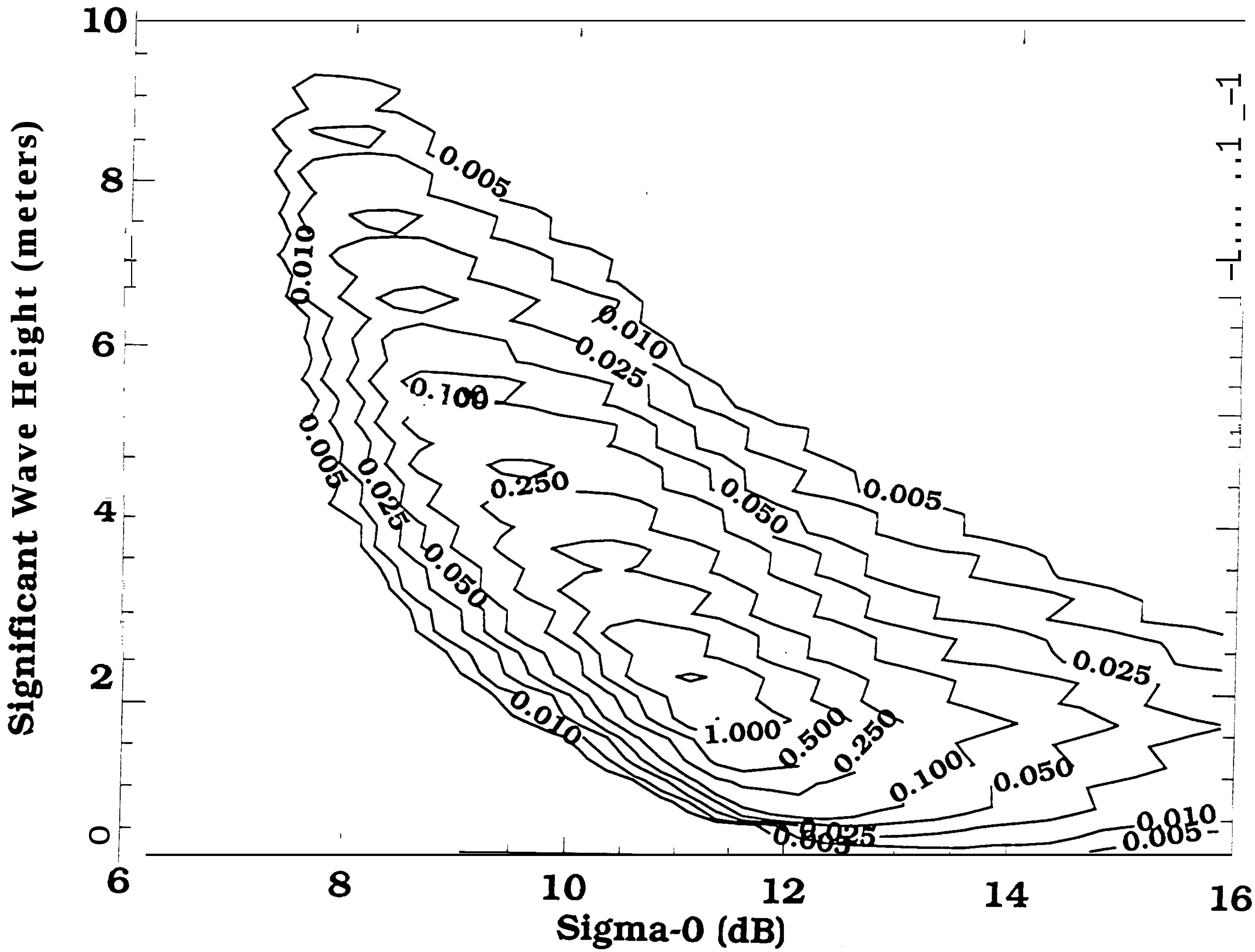


January Sigma-0: -60 to +60
February Sigma-0: -60 to +60
March Sigma-0: -60 to +60
April Sigma-0: -60 to +60
May Sigma-0: -60 to +60
June Sigma-0: -60 to +60
Percent of Ocean Observations
Sigma-0 (dB)
Sigma-0 dB
0
1
2
3
4
5
8
10
12
14
16


Figure 3

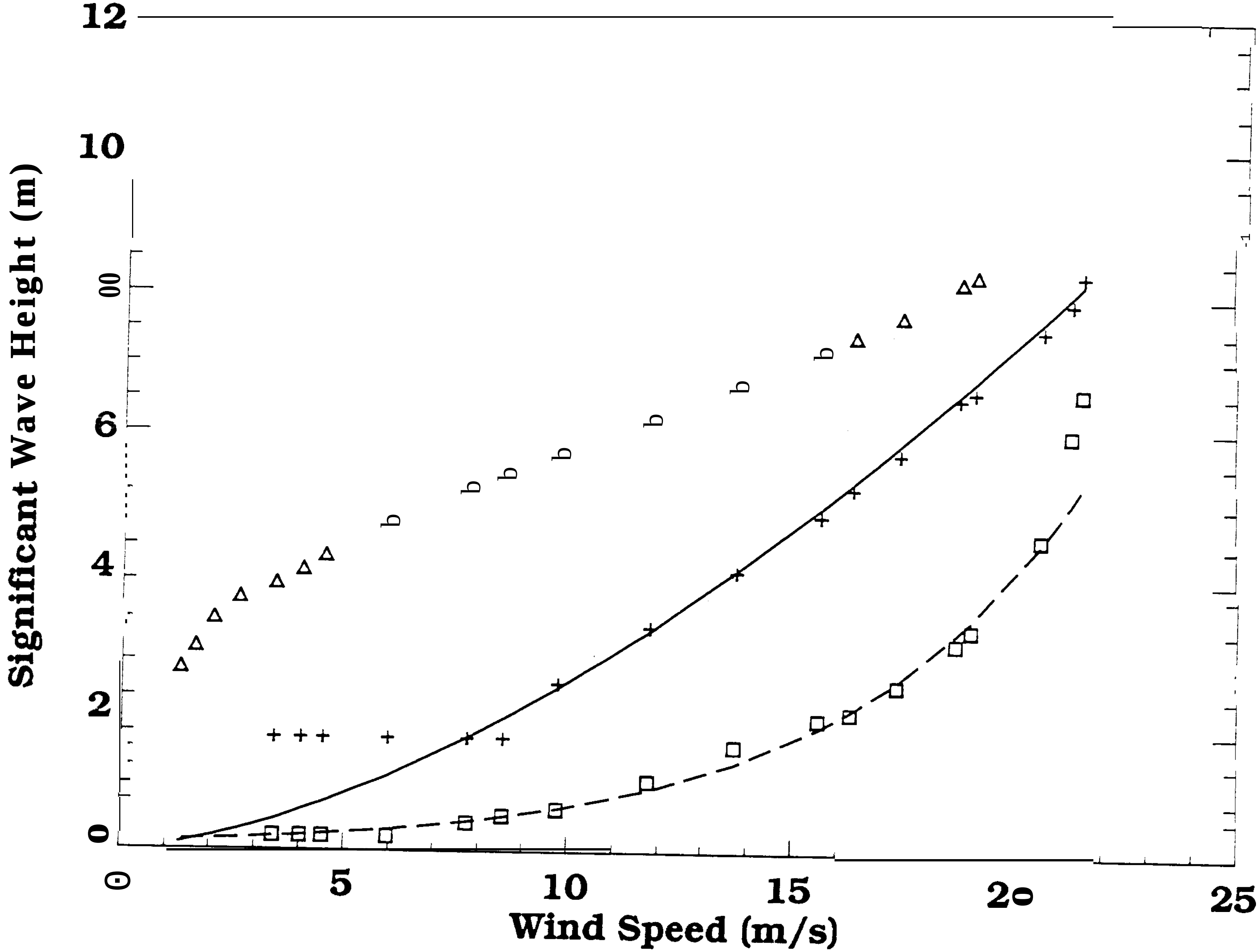

January Sigma-O: +20 to +60
March Sigma-0: +20 to +60
June Sigma-O: +20 to +60
January Sigma-O: -20 to +20
March Sigma-O: -20 to +20
June Sigma-O: -20 to +20
January Sigma-O: -60 to -20
March Sigma-O: -60 to -20
June Sigma-O: -60 to -20
Percent of Ocean Observations
Sigma-O (dB)

Figure



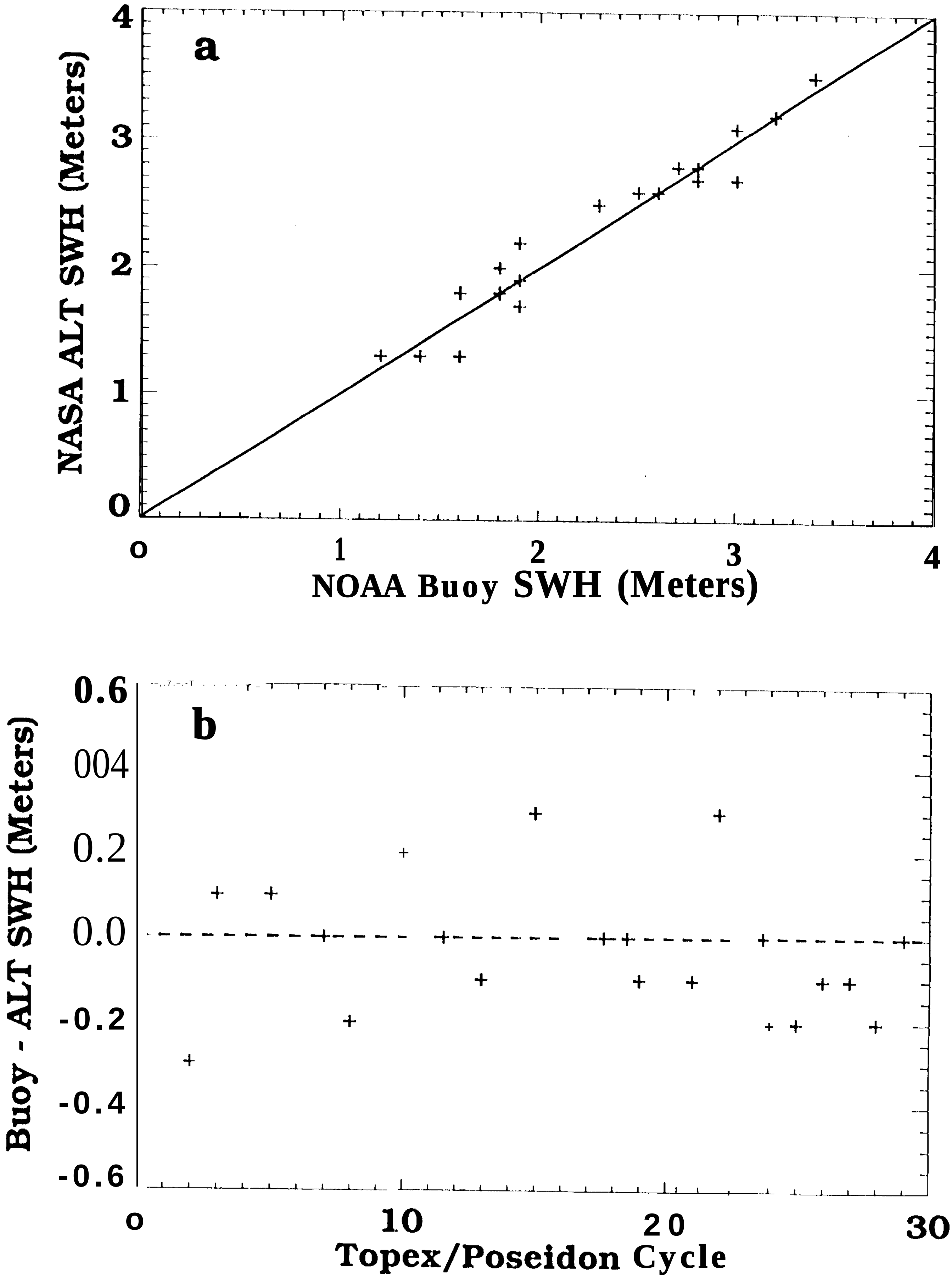
Significant Wave Height (meters)
Sigma-0 (dB)
0.005
0.010
0.025
0.050
0.100
0.250
0.500
1.000


Figure 5



Significant Wave Height (m)
0
2
4
6
00
10
12
Wind Speed (m/s)
0
5
10
15
20
25


Figure 6


a
4
3
2
1
0
NASA ALT SWH (Meters)
o
1
2
3
4
NOAA Buoy SWH (Meters)
b
0.6
004
0.2
0.0
-0.2
-0.4
-0.6
Buoy - ALT SWH (Meters)
o
10
20
30
Topex/Poseidon Cycle

a

b

Figure 7

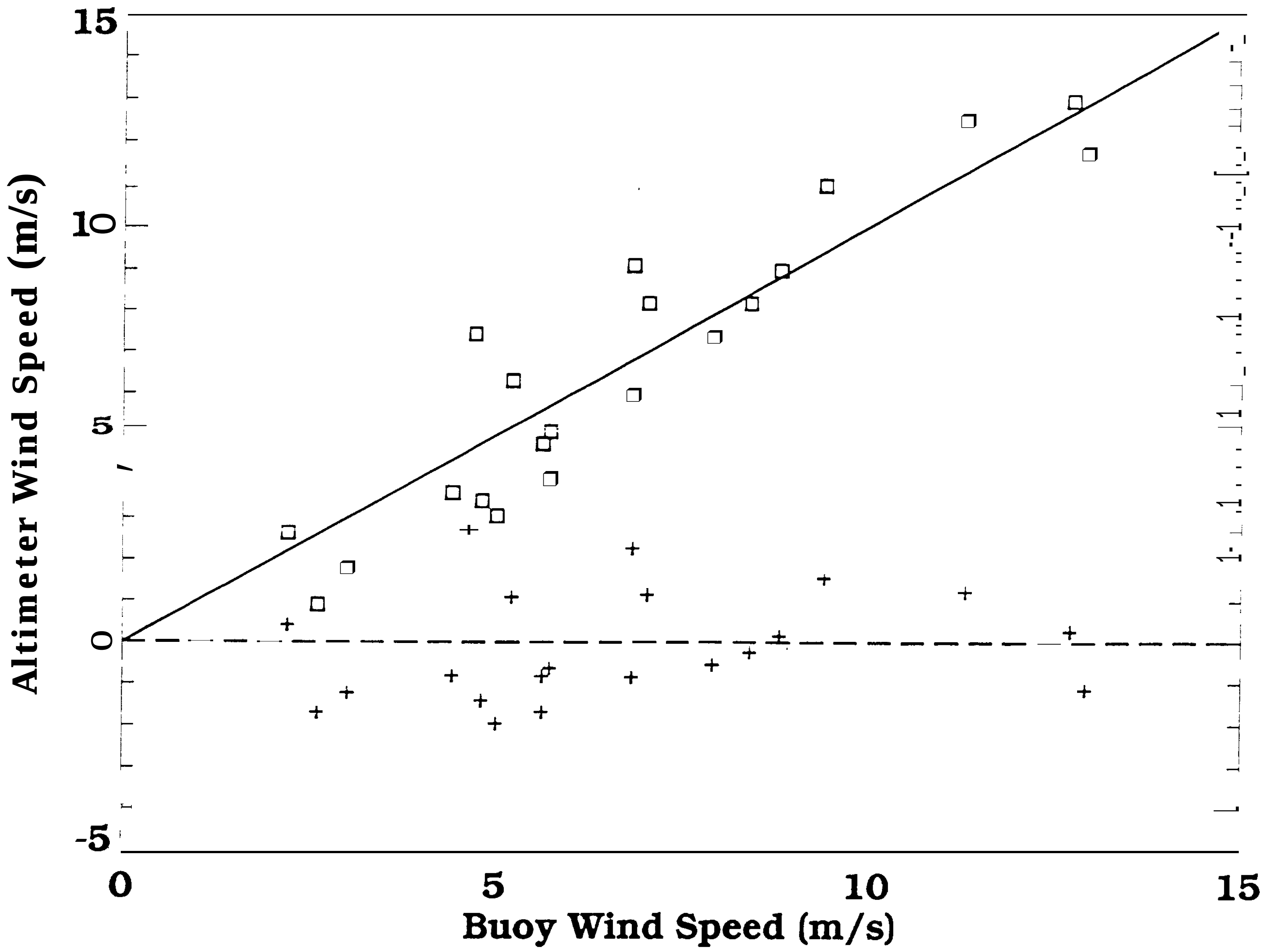



Figure 7c